

THERMAL BARRIER COATINGS WITH PROTECTIVE OUTER LAYER FOR
IMPROVED IMPACT AND EROSION RESISTANCE

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0001] This invention was made with Government support under Contract No. N00019-96-C-0176 awarded by the JSF Program Office. The Government has certain rights to the invention.

BACKGROUND OF THE INVENTION

[0002] This invention relates to improving the impact and erosion resistance of thermal barrier coatings having reduced thermal conductivity. This invention further relates to articles having such coatings and methods for preparing such coatings for the article.

[0003] Components operating in the gas path environment of gas turbine engines are typically subjected to significant temperature extremes and degradation by oxidizing and corrosive environments. Environmental coatings and especially thermal barrier coating are an important element in current and future gas turbine engine designs, as well as other articles that are expected to operate at or be exposed to high temperatures, and thus cause the thermal barrier coating to be subjected to high surface temperatures. Examples of turbine engine parts and components for which such thermal barrier coatings are desirable include turbine blades and vanes, turbine shrouds, buckets, nozzles, combustion liners and deflectors, and the like. These thermal barrier coatings typically comprise the external portion or surface of these components are usually deposited onto a metal substrate (or more typically onto a bond coat layer on the metal substrate for better adherence) from which the part or component is formed to reduce heat flow (i.e., provide thermal insulation) and to limit (reduce) the operating temperature the underlying metal substrate of these parts and components is subjected to. This metal substrate typically comprises a metal alloy such as a nickel, cobalt, and/or iron based alloy (e.g., a high temperature superalloy).

[0004] The thermal barrier coating is usually prepared from a ceramic material, such as a chemically (metal oxide) stabilized zirconia. Examples of such chemically phase-stabilized zirconias include yttria-stabilized zirconia, scandia-stabilized zirconia, calcia-stabilized zirconia, and magnesia-stabilized zirconia. The

thermal barrier coating of choice is typically a yttria-stabilized zirconia ceramic coating. A representative yttria-stabilized zirconia thermal barrier coating usually comprises about 7 weight % yttria and about 93 weight % zirconia. The thickness of the thermal barrier coating depends upon the metal part or component it is deposited on, but is usually in the range of from about 3 to about 70 mils (from about 76 to about 1778 microns) thick for high temperature gas turbine engine parts.

[0005] Although significant advances have been made in improving the durability of thermal barrier coatings for turbine engine components, such coatings are still susceptible to various types of damage, including objects ingested by the engine, erosion, oxidation, and attack from environmental contaminants. In addition, in trying to achieve reduced thermal conductivity, other properties of the thermal barrier coating can be adversely impacted. For example, the composition and crystalline microstructure of a thermal barrier coating, such as those prepared from yttria-stabilized zirconia, can be modified to impart to the coating an improved reduction in thermal conductivity, especially as the coating ages over time. However, such modifications can also unintentionally interfere with desired thermal spallation resistance, as well as resistance to particle erosion, especially at the higher temperatures that most turbine components are subjected to. As a result, the thermal barrier coating can become more susceptible to damage due to the impact of, for example, objects and debris ingested by the engine and passing through the turbine sections thereof, as well as erosion due to small particles and sand.

[0006] Accordingly, it would be desirable to be able to improve the impact and erosion resistance of thermal barrier coatings having reduced thermal conductivity. It would be further desirable to be able to modify the chemical composition of yttria-stabilized zirconia-based thermal barrier coating systems to provide such reduced thermal conductivity, yet still retain at least acceptable impact and erosion resistance in such coatings.

BRIEF DESCRIPTION OF THE INVENTION

[0007] An embodiment of this invention relates to improving the impact and erosion resistance of a thermal barrier coating having reduced thermal conductivity that is used with the underlying metal substrate of articles that operate at, or are exposed to, high temperatures. This thermal barrier coating comprises:

1. an inner layer nearest to and overlaying the metal substrate and comprising a ceramic thermal barrier coating material; and
2. a protective outer layer adjacent to and overlaying the inner layer and having an exposed surface, the outer layer having a thickness up to about 5 mils (127 microns) and sufficient to impart impact and erosion resistance to the thermal barrier coating, and comprising a zirconia-containing ceramic composition having a c/a ratio of the zirconia lattice in the range of from about 1.011 to about 1.016 and stabilized in the tetragonal phase by a stabilizing amount of a stabilizing metal oxide selected from the group consisting of yttria, calcia, ceria, scandia, magnesia, indium, ytterbia and mixtures thereof.

[0008] Another embodiment of this invention relates to a thermally protected article. This protected article comprises:

- A. a metal substrate;
- B. optionally a bond coat layer adjacent to and overlaying the metal substrate; and
- C. a thermal barrier coating (as previously described) adjacent to and overlaying the bond coat layer (or overlaying the metal substrate if the bond coat layer is absent).

[0009] Another embodiment of this invention relates to a method for preparing the thermal barrier coating on a metal substrate to provide a thermally protected article. This method comprises the steps of:

- A. optionally forming a bond coat layer on the metal substrate;
- B. depositing on the bond coat layer (or on the metal substrate in the absence of the bond coat layer) the ceramic thermal barrier coating material to form the inner layer; and
- C. forming on the inner layer the protective outer layer as previously described.

[0010] The thermal barrier coatings of this invention provide several significant benefits when used with metal substrates of articles exposed to high temperatures, such as turbine components. The thermal barrier coatings of this invention provide a desirable balance of reduced thermal conductivity for the

thermally protected article with improved impact and erosion resistance. This improvement in impact and erosion resistance for the thermal barrier coating can be achieved while allowing flexibility in using a variety of zirconia-containing ceramic compositions that can impart to the thermal barrier coating desirable reduced thermal conductivity properties.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a partial side sectional view of an embodiment of the thermal barrier coating and coated article of this invention.

[0012] FIG. 2 represents a graphical plot of calculated c/a ratios of the zirconia lattice as a function of yttria content.

DETAILED DESCRIPTION OF THE INVENTION

[0013] As used herein, the term "ceramic thermal barrier coating materials" refers to those coating materials that are capable of reducing heat flow to the underlying metal substrate of the article, i.e., forming a thermal barrier, and which have a melting point that is typically at least about 2600°F (1426°C), and more typically in the range of from about 3450° to about 4980°F (from about 1900° to about 2750°C). Suitable ceramic thermal barrier coating materials for use herein include, aluminum oxide (alumina), i.e., those compounds and compositions comprising Al_2O_3 , including unhydrated and hydrated forms, various zirconias, in particular chemically phase-stabilized zirconias (i.e., various metal oxides such as yttrium oxides blended with zirconia), such as yttria-stabilized zirconias, ceria-stabilized zirconias, calcia-stabilized zirconias, scandia-stabilized zirconias, magnesia-stabilized zirconias, india-stabilized zirconias, ytterbia-stabilized zirconias as well as mixtures of such stabilized zirconias. See, for example, Kirk-Othmer's Encyclopedia of Chemical Technology, 3rd Ed., Vol. 24, pp. 882-883 (1984) for a description of suitable zirconias. Suitable yttria-stabilized zirconias can comprise from about 1 to about 20% yttria (based on the combined weight of yttria and zirconia), and more typically from about 3 to about 10% yttria. These chemically phase-stabilized zirconias can further include one or more of a second metal (e.g., a lanthanide or actinide) oxide such as dysprosia, erbia, europia, gadolinia, neodymia, praseodymia, urania, and hafnia to further reduce thermal conductivity of the thermal barrier coating. See U.S. Pat. No. 6,025,078 (Rickerby et al), issued February 15,

2000 and U.S. Pat. No. 6,333,118 (Alperine et al), issued December 21, 2001, both of which are incorporated by reference. Suitable ceramic thermal barrier coating materials also include pyrochlores of general formula $A_2B_2O_7$ where A is a metal having a valence of 3+ or 2+ (e.g., gadolinium, aluminum, cerium, lanthanum or yttrium) and B is a metal having a valence of 4+ or 5+ (e.g., hafnium, titanium, cerium or zirconium) where the sum of the A and B valences is 7. Representative materials of this type include gadolinium-zirconate, lanthanum titanate, lanthanum zirconate, yttrium zirconate, lanthanum hafnate, cerium zirconate, aluminum cerate, cerium hafnate, aluminum hafnate and lanthanum cerate. See U.S. Pat. No. 6,117,560 (Maloney), issued September 12, 2000; U.S. Pat. No. 6,177,200 (Maloney), issued January 23, 2001; U.S. Pat. No. 6,284,323 (Maloney), issued September 4, 2001; U.S. Pat. No. 6,319,614 (Beele), issued November 20, 2001; and U.S. Pat. No. 6,387,526 (Beele), issued May 14, 2002, all of which are incorporated by reference.

[0014] Suitable ceramic compositions for use herein are also disclosed in copending U.S. nonprovisional applications entitled "CERAMIC COMPOSITIONS USEFUL FOR THERMAL BARRIER COATINGS HAVING REDUCED THERMAL CONDUCTIVITY" (Spitsberg et al), Serial No. _____, filed _____, 2003, Attorney Docket No. 129967, and "CERAMIC COMPOSITIONS USEFUL IN THERMAL BARRIER COATINGS HAVING REDUCED THERMAL CONDUCTIVITY" (Spitsberg et al), Serial No. _____, filed _____, 2003, Attorney Docket No. 129968, both of which are incorporated by reference. The ceramic compositions disclosed in the first of these copending applications comprise at least about 91 mole % zirconia and up to about 9 mole % of a stabilizer component comprising a first metal oxide having selected from the group consisting of yttria, calcia, ceria, scandia, magnesia, india, ytterbia and mixtures thereof; a second metal oxide of a trivalent metal atom selected from the group consisting of lanthana, gadolinia, neodymia, samaria, dysprosia, and mixtures thereof; and a third metal oxide of a trivalent metal atom selected from the group consisting of erbia, ytterbia and mixtures thereof. Typically, these ceramic compositions comprise from about 91 to about 97 mole % zirconia, more typically from about 92 to about 95 mole % zirconia and from about 3 to about 9 mole %, more typically from about 5 to about 8 mole %, of the composition of the

stabilizing component; the first metal oxide (typically yttria) can comprise from about 3 to about 6 mole %, more typically from about 3 to about 5 mole %, of the ceramic composition; the second metal oxide (typically lanthana or gadolinia) can comprise from about 0.25 to about 2 mole %, more typically from about 0.5 to about 1.5 mole %, of the ceramic composition; and the third metal oxide (typically ytterbia) can comprise from about 0.5 to about 2 mole %, more typically from about 0.5 to about 1.5 mole %, of the ceramic composition, with the ratio of the second metal oxide to the third metal oxide typically being in the range of from about 0.5 to about 2, more typically from about 0.75 to about 1.33.

[0015] The ceramic compositions disclosed in the second of these copending applications comprise at least about 91 mole % zirconia and up to about 9 mole % of a stabilizer component comprising a first metal oxide having selected from the group consisting of yttria, calcia, ceria, scandia, magnesia, india and mixtures thereof and a second metal oxide of a trivalent metal atom selected from the group consisting of lanthana, gadolinia, neodymia, samaria, dysprosia, erbia, ytterbia, and mixtures thereof. Typically, these ceramic compositions comprise from about 91 to about 97 mole % zirconia, more typically from about 92 to about 95 mole % zirconia and from about 3 to about 9 mole %, more typically from about 5 to about 8 mole %, of the composition of the stabilizing component; the first metal oxide (typically yttria) can comprise from about 3 to about 6 mole %, more typically from about 4 to about 5 mole %, of the ceramic composition; the second metal oxide (typically lanthana, gadolinia or ytterbia, and more typically lanthana) can comprise from about 0.5 to about 4 mole %, more typically from about 0.8 to about 2 mole %, of the ceramic composition, and wherein the mole % ratio of second metal oxide (e.g., lanthana/gadolinia/ytterbia) to first metal oxide (e.g., yttria) is in the range of from about 0.1 to about 0.5, typically from about 0.15 to about 0.35, more typically from about 0.2 to about 0.3.

[0016] As used herein, the term “fraction of porosity” refers to the volume fraction of porosity defined by unity (i.e., 1), minus the ratio of the actual density of the thermal barrier coating to its theoretical density.

[0017] As used herein, the term “comprising” means various compositions, compounds, components, layers, steps and the like can be conjointly employed in the

present invention. Accordingly, the term "comprising" encompasses the more restrictive terms "consisting essentially of" and "consisting of."

[0018] All amounts, parts, ratios and percentages used herein are in wt. % unless otherwise specified.

[0019] Thermal barrier coatings of this invention are useful with a wide variety of turbine engine (e.g., gas turbine engine) parts and components that are formed from metal substrates comprising a variety of metals and metal alloys, including superalloys, and are operated at, or exposed to, high temperatures, especially higher temperatures that occur during normal engine operation. These turbine engine parts and components can include turbine airfoils such as blades and vanes, turbine shrouds, turbine nozzles, combustor components such as liners and deflectors, augmentor hardware of gas turbine engines and the like. The thermal barrier coatings of this invention can also cover a portion or all of the metal substrate. For example, with regard to airfoils such as blades, the thermal barrier coatings of this invention are typically used to protect, cover or overlay portions of the metal substrate of the airfoil rather than the entire component, e.g., the thermal barrier coatings could cover the leading edge, possibly part of the trailing edge, but not the attachment area. While the following discussion of the thermal barrier coatings of this invention will be with reference to metal substrates of turbine engine parts and components, it should also be understood that the thermal barrier coatings of this invention are useful with metal substrates of other articles that operate at, or are exposed to, high temperatures.

[0020] The various embodiments of the thermal barrier coatings of this invention are further illustrated by reference to the drawings as described hereafter. Referring to the drawings, FIG. 1 shows a side sectional view of an embodiment of the thermally barrier coating used with the metal substrate of an article indicated generally as 10. As shown in FIG. 1, article 10 has a metal substrate indicated generally as 14. Substrate 14 can comprise any of a variety of metals, or more typically metal alloys, that are typically protected by thermal barrier coatings, including those based on nickel, cobalt and/or iron alloys. For example, substrate 14 can comprise a high temperature, heat-resistant alloy, e.g., a superalloy. Such high temperature alloys are disclosed in various references, such as U.S. Pat. No.

5,399,313 (Ross et al), issued March 21, 1995 and U.S. Pat. No. 4,116,723 (Gell et al), issued September 26, 1978, both of which are incorporated by reference. High temperature alloys are also generally described in Kirk-Othmer's Encyclopedia of Chemical Technology, 3rd Ed., Vol. 12, pp. 417-479 (1980), and Vol. 15, pp. 787-800 (1981). Illustrative high temperature nickel-based alloys are designated by the trade names Inconel®, Nimonic®, René® (e.g., René® 80-, René® N5 alloys), and Udimet®. As described above, the type of substrate 14 can vary widely, but it is representatively in the form of a turbine part or component, such as an airfoil (e.g., blade) or turbine shroud.

[0021] As shown in FIG. 1, article 10 can also include a bond coat layer indicated generally as 18 that is adjacent to and overlies substrate 14. Bond coat layer 18 is typically formed from a metallic oxidation-resistant material that protects the underlying substrate 14 and enables the thermal barrier coating indicated generally as 22 to more tenaciously adhere to substrate 14. Suitable materials for bond coat layer 18 include overlay bond coatings such MCrAlY alloys (e.g., alloy powders), where M represents a metal such as iron, nickel, platinum or cobalt, or NiAl(Zr) overlay coatings, as well as various noble metal diffusion aluminides such as platinum aluminide, as well as simple aluminides (i.e., those formed without noble metals) such as nickel aluminide. This bond coat layer 18 can be applied, deposited or otherwise formed on substrate 10 by any of a variety of conventional techniques, such as electroless plating, physical vapor deposition (PVD), including electron beam physical vapor deposition (EB-PVD), plasma spray, including air plasma spray (APS) and vacuum plasma spray (VPS), ion plasma, or other thermal spray deposition methods such as high velocity oxy-fuel (HVOF) spray, detonation, or wire spray, chemical vapor deposition (CVD), pack cementation and vapor phase aluminiding in the case of metal diffusion aluminides (see, for example, U.S. Pat. No. 4,148,275 (Benden et al), issued April 10, 1979; U.S. Pat. No. 5,928,725 (Howard et al), issued July 27, 1999; and U.S. Pat. No. 6,039,810 (Mantkowski et al), issued March 21, 2000, all of which are incorporated by reference and which disclose various apparatus and methods for applying diffusion aluminide coatings), and combinations thereof. Typically, if a plasma spray or diffusion technique is employed to deposit bond coat layer 18, the thickness is in the range of from about 1 to about 20 mils (from about 25

to about 508 microns). For bond coat layers 18 deposited by PVD techniques such as EB-PVD or diffusion aluminide processes, the thickness is more typically in the range of from about 1 to about 3 mils (from about 25 to about 76 microns).

[0022] As shown in FIG. 1, thermal barrier coating (TBC) 22 of this invention is adjacent to and overlies bond coat layer 18. The thickness of TBC 22 is typically in the range of from about 1 to about 100 mils (from about 25 to about 2540 microns) and will depend upon a variety of factors, including the design parameters for article 10 that are involved. For example, for turbine shrouds, TBC 22 is typically thicker and is usually in the range of from about 30 to about 70 mils (from about 762 to about 1778 microns), more typically from about 40 to about 60 mils (from about 1016 to about 1524 microns). By contrast, in the case of turbine blades, TBC 22 is typically thinner and is usually in the range of from about 3 to about 30 mils (from about 76 to about 762 microns), more typically from about 3 to about 10 mils (from about 76 to about 254 microns).

[0023] As shown in the FIG. 1, TBC 22 comprises an inner layer 26 that is nearest to substrate 14, and is adjacent to and overlies bond coat layer 18. This inner layer 26 comprises a ceramic thermal barrier coating material (as previously described) and will normally comprise most of the thickness of TBC 22. Typically, inner layer 26 will comprise from about 50 to about 95%, more typically from about 70 to about 85%, of the thickness of TBC 22.

[0024] TBC 22 further comprises a protective outer layer indicated generally as 30 that is adjacent to and overlies inner layer 26 and has an exposed surface 34. This outer layer 30 of TBC 22 typically forms a relatively thin protective layer that improves the impact and erosion resistance of TBC 22 and especially inner layer 26. The thickness of outer layer 30 should be such as to provide impact and erosion resistant, without unduly affecting the other (e.g., mechanical and thermal insulating) properties of TBC 22, including strain tolerance, modulus and thermal conductivity. In this regard, outer layer 30 should be relatively thin and have a thickness up to about 5 mils (127 microns). Typically, the thickness of outer layer 30 is in the range of from about 0.5 to about 2 mils (from about 13 to about 51 microns), more typically from about 1 to about 2 mils (from about 25 to about 51 microns).

[0025] The outer layer 30 of TBCs 22 of this invention comprises a zirconia-

containing ceramic composition that is stabilized in a certain region of the tetragonal phase to impart improved impact and erosion resistance properties for TBC 22. The impact and erosion resistance properties of these outer layers 30 can be predicted on the basis of the effect of the zirconia lattice stability equivalent of the respective zirconia-containing ceramic compositions. Impact and erosion resistance performance have been found to be related to the zirconia lattice stability equivalent. This stability equivalent can be calculated based on the ratio of the zirconia lattice parameters c and a using equation (1) below:

$$\frac{c}{a} = k_1 \sum_i (r_i - r_{Zr}) \times m_i + k_2 \sum_i (V_i - V_{Zr}) \times m_i \quad (1)$$

wherein c, a are the zirconia tetragonal lattice parameters, r_i is the ionic radius of the first metal oxide, V_i is the valence of the metal ion of the metal oxide added, m_i is the mole fraction of the metal oxide added and k_1 and k_2 are constants. See Kim, "Effect of Ta_2O_5 , Nb_2O_5 , and HfO_2 Alloying on the Transformability of Y_2O_3 -Stabilized Tetragonal ZrO_2 ," J.Am. Ceram. Soc., (1990) 73 (1) pp. 115-120.

[0026] Using equation (1) above, the lattice stability of these zirconia-containing ceramic compositions in the tetragonal phase can be calculated, including the effect of incremental additions of the stabilizing metal oxide, such as yttria. This is illustrated by FIG. 2 which represents a graphical plot of calculated c/a ratios for the zirconia lattice as a function of yttria content. The dotted line (base line) in FIG. 2 represents a zirconia-containing-ceramic composition stabilized with the equivalent of about 7 wt. % yttria (7YSZ) that has a c/a ratio of about 1.012. As also shown in FIG. 2, as the level of yttria decreases in the zirconia-containing ceramic composition, the c/a ratio conversely increases. It has been further found that, as the c/a ratio increases, impact and erosion resistance improves, i.e., lowering the yttria level improves the impact and erosion resistance performance of the zirconia-containing ceramic composition.

[0027] To provide outer protective layers 30 having suitable impact and erosion resistance performance, zirconia-containing-ceramic composition should have a c/a ratio that is typically in the range of from about 1.011 to about 1.016, more

typically in the range of from about 1.013 to about 1.015. Suitable zirconia-containing compositions for use in outer layer 30 that have these c/a ratios can comprise at least about 90 wt. % zirconia. Typically, these zirconia-containing compositions comprise from about 93 to about 96 wt. % zirconia, more typically from about 93.5 to about 95.5 wt. % zirconia. Suitable zirconia-containing compositions for use in outer layer 30 that have these c/a ratios further comprise a stabilizing amount of a stabilizing metal oxide. Typically, the stabilizing metal oxide is included in an amount of from about 4 to about 7 wt. % of the composition. Suitable stabilizing metal oxides can be selected from the group consisting of yttria, calcia, ceria, scandia, magnesia, india and mixtures thereof. The zirconia-containing ceramic compositions useful in outer layer 30 typically comprise yttria as the stabilizing metal oxide in an amount from about 4.5 to about 6.5 wt. % of the composition.

[0028] While the c/a ratio of the zirconia-containing composition has a strong effect on erosion resistance performance, and an especially strong effect on impact resistance performance, it has been further found that the porosity level of the resultant outer layer 30 of TBC 22 has an effect as well. Accordingly, additional impact and erosion resistance benefits can be obtained by optionally making outer layer 30 denser, i.e., by reducing its porosity. This is typically achieved by forming outer layer 30 so as to have a fraction of porosity of about 0.20 or less, more typically about 0.15 or less. Typically outer layer 30 has a fraction of porosity of from about 0.10 to about 0.20, more typically from about 0.10 to about 0.15.

[0029] Further impact and erosion resistance benefits can be obtained by optionally having present in outer layer 30 up to about 10 wt. % hafnia. Typically, hafnia is present in outer layer 30 in an amount of from about 2 to about 7 wt. %, more typically from about 4 to about 6 wt. %. Other metal oxides, such as lanthana, neodymia, gadolinia and mixtures thereof can also be optionally present in outer layer 30 in amounts up to about 1 wt. %, more typically in the range of from about 0.3 to about 0.5 wt. %. Suitable zirconia-containing ceramic compositions that comprise hafnia and/or these other metal oxides include those shown in the following Table 1:

Table 1

Metal Oxide (Wt. %)	Composition 1	Composition 2	Composition 3
Zirconia	91.6	95.5	95.6
Yttria	4.0	4.0	4.0
Hafnia	4.4		
Lanthana		0.5	
Neodymia			0.4

[0030] Referring to the FIG. 1, the inner layer 26 of TBC 22 can be applied, deposited or otherwise formed on bond coat layer 18 by any of a variety of conventional techniques, such as wet plating, physical vapor deposition (PVD), including electron beam physical vapor deposition (EB-PVD), plasma spray, including air plasma spray (APS) and vacuum plasma spray (VPS), or other thermal spray deposition methods such as high velocity oxy-fuel (HVOF) spray, detonation, or wire spray; chemical vapor deposition (CVD), or combinations thereof. The particular technique used for applying, depositing or otherwise forming inner layer 26 will typically depend on the composition of inner layer 26, its thickness and especially the physical structure desired for TBC. For example, PVD techniques tend to be useful in forming TBCs having a strain-tolerant columnar structure. By contrast, plasma spray techniques (e.g., APS) tend to create a sponge-like porous structure of open pores in at least inner layer 26. Inner layer 26 of TBC 22 is typically formed from ceramic thermal barrier coating materials by PVD and especially EB-PVD techniques to provide a strain-tolerant columnar structure.

[0031] Various types of PVD and especially EB-PVD techniques well known to those skilled in the art can also be utilized to form inner layer 26 of the TBCs 22 of this invention. See, for example, U.S. Pat. No. 5,645,893 (Rickerby et al), issued July 8, 1997 (especially col. 3, lines 36-63); U.S. Pat. No. 5,716,720 (Murphy), issued February 10, 1998 (especially col. 5, lines 24-61) and U.S. Pat. No. 6,447,854 (Rigney et al), issued September 10 2002, which are incorporated by reference. Suitable EB-PVD techniques for use herein typically involve a coating chamber with a gas (or gas mixture) that preferably includes oxygen and an inert gas, though an

oxygen-free coating atmosphere can also be employed. The ceramic thermal barrier coating materials are then evaporated with electron beams focused on, for example, ingots of the ceramic thermal barrier coating materials so as to produce a vapor of metal ions, oxygen ions and one or more metal oxides. The metal and oxygen ions and metal oxides recombine to form inner layer 26 of TBC 22 on the surface of metal substrate 14, or more typically on bond coat layer 18.

[0032] Various types of plasma-spray techniques well known to those skilled in the art can also be utilized to form inner layer 26 of TBCs 22 of this invention. See, for example, Kirk-Othmer Encyclopedia of Chemical Technology, 3rd Ed., Vol. 15, page 255, and references noted therein, as well as U.S. Pat. No. 5,332,598 (Kawasaki et al), issued July 26, 1994; U.S. Pat. No. 5,047,612 (Savkar et al) issued September 10, 1991; and U.S. Pat. No. 4,741,286 (Itoh et al), issued May 3, 1998 (herein incorporated by reference) which are instructive in regard to various aspects of plasma spraying suitable for use herein. In general, typical plasma spray techniques involve the formation of a high-temperature plasma, which produces a thermal plume. The ceramic coating composition, e.g., ceramic powders, are fed into the plume, and the high-velocity plume is directed toward the bond coat layer 18. Various details of such plasma spray coating techniques will be well-known to those skilled in the art, including various relevant steps and process parameters such as cleaning of the bond coat surface 18 prior to deposition; grit blasting to remove oxides and roughen the surface substrate temperatures, plasma spray parameters such as spray distances (gun-to-substrate), selection of the number of spray-passes, powder feed rates, particle velocity, torch power, plasma gas selection, oxidation control to adjust oxide stoichiometry, angle-of-deposition, post-treatment of the applied coating; and the like. Torch power can vary in the range of about 10 kilowatts to about 200 kilowatts, and in preferred embodiments, ranges from about 40 kilowatts to about 60 kilowatts. The velocity of the ceramic coating composition particles flowing into the plasma plume (or plasma "jet") is another parameter which is usually controlled very closely. Suitable plasma spray systems are described in, for example, U.S. Pat. No. 5,047,612 (Savkar et al) issued September 10, 1991, which is incorporated by reference.

[0033] The outer protective layer 30 of TBC 22 can be applied, deposited or otherwise formed on inner layer 26 by any of the techniques previously described for

forming inner layer 26 on bond coat layer 18. Typically, outer layer 30 is formed by depositing a zirconia-containing ceramic composition as previously described on the inner layer 26 by PVD, and especially EB-PVD, techniques. The difference in the PVD, and especially EB-PVD techniques, that are used to deposit outer protective layer 30 (versus inner layer 26) relate to those parameters, in particular pressure and/or temperature, that can be varied (e.g., by reducing the pressure) to reduce the porosity of outer layer 30 during formation thereof.

[0034] While specific embodiments of the method of the present invention have been described, it will be apparent to those skilled in the art that various modifications thereto can be made without departing from the spirit and scope of the present invention as defined in the appended claims.